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COMPARATIVE STUDY OF THE LONG-TERM DEFLECTION OF CONVENTIONAL AND SELF-COMPACTING CONCRETE WITH LIGHT-WEIGHT CONCRETE SLABS

By

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CERTIFICATE OF AUTHORSHIP/ORIGINALITY

I certify that the work in this thesis has not previously been submitted for a degree nor has it been submitted as part of requirements for a degree except as fully acknowledged within the text. I also certify that the thesis has been written by me. Any help that I have received in my research work and the preparation of the thesis itself has been acknowledged. In addition, I certify that all information sources and literature used are indicated in the thesis.

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Notations

The symbols used in this study. Including their definitions, are listed below.

AASHTO	American Association of State Highway and Transportation Officials
ACI	American Concrete Institute
AEA	Air-Entraining Agent
ALWAC	All Light-Weight Aggregate Concrete
AS	Australian standard
ASTM	American Society for Testing and Materials
A_{cr}	Area of section at first cracking
A_e	Effective section area under direct tension
A_g	Gross cross section area
A_{st}	Area of tensile steel bar
BST	Commercial name for the spherical-shaped polystyrene beads with hydrophilic type chemical coating
CC	Conventional concrete
CS	Compressive Strength
CS.CUBE	Compressive strength of cube specimen
CSH	Calcium Silicate Hydrates
CS.CYL	Compressive strength of cylindrical specimen
CSSC	Compressive stress-strain curve
Cyl.	Cylinder
C_b	Concrete cover of bar to the soffit of member
C_m	Smaller of clear bottom cover in reinforced concrete
c/p	Cement to powder ratio
C_s	Concrete cover of bar to the side surface of member
DL	Dead load
D-SCC	Self-compacting concrete containing steel fibre
DS-SCC	Self-compacting concrete containing hybrid fibre (steel and Polypropylene fibre)
D_0^{el}	Initial (undamaged) elastic stiffness of the material
d	Effective depth of tensile bar
dia.	Diameter
d_b	Bar diameter
ECC	Engineered Cementitious Composite
EI	Bending stiffness
EPS	Expanded Poly-Styrene
EPS-LWC	Light Weight Concrete containing Expanded Poly-Styrene Beads
E_c	Modulus of elasticity of concrete

E_{c-14}	Modulus of elasticity of concrete at age 14 days
E_{c-28}	Modulus of elasticity of concrete at age 28 days
E_f	Modulus of elasticity of fibre
E_p	Final slope of the compressive stress-strain curve
E_s	Modulus of elasticity of steel bars
E_0	Initial slope of the compressive stress-strain curve
F	Axial tension in pull out test
FEA	Finite Element Analysis
FHWA	Federal Highway Administration
FRP	Fibre reinforced polymer
FRSCC	Fibre reinforced self-compacting concrete
f_{ck}	Specified compressive strength of concrete
f_{cm}	Mean concrete cylinder compressive strength
f_{ct}	Splitting tensile strength of concrete
f_{ct-28}	Splitting tensile strength of concrete at age 28 days
f_{cu}	Specified characteristic cube compressive strength
$F_{d.ef}$	Effective design load, per unit area
f_r	Modulus of rupture (flexural tensile strength)
f_{rel}	Relative compressive strength
f_{r-28}	Modulus of rupture at age 28 days
f_s	estimated design service stress in tension reinforcement
f_t	Splitting tensile strength
ft.	Foot
f_y	yield strength of reinforcement
f_{yt}	Yield stress of tensile bar
$f(t)$	Time-function parameter
f_c'	Compressive strength of concrete
$f_t'^{\,ef}$	Effective tensile strength derived from the biaxial failure function of concrete
GGBFS	Ground Granulated Blast Furnace Slag
gr	Gram
GPa	Giga Pascal
G_c	Absorbed energy per unit volume of the cylindrical specimens under compression
G_{c-28}	Absorbed energy per unit volume of the cylindrical specimens under compression at age 28 days
G_f	Fracture energy needed to create a unit area of stress-free crack
G_{Fi}	Average energy required for unit crack propagation from crack initiation until any time
HPFRC	High-Performance Fibre Reinforced Concrete
HRWRA	High Range Water Reducing Admixture
HSLWC	High-Strength Light-Weight Concrete
HSNWC	High-Strength Normal-Weight Concrete
h_r	Rib height in steel bar

I_{cr}	Moment of inertia of section at first cracking
I_e	Effective moment of inertia
I_g	gross moment of inertia of uncracked reinforced concrete section
I_m	Average moment of inertia of section in span length
$J(t, t_0)$	Compliance function of concrete
LEFM	Linear Elastic Fracture Mechanics
l	Span length
lb	pound
lb/ft^3	Pound per cubic feet
Lit/m^3	Litre per cubic metre
LL_1	Loading level 1 (Lower loading level)
LL_2	Loading level 2 (Upper loading level)
LVDT	Linear variable differential transformer
LWC	Light weight concrete
LWCC	Light-Weight Ceramic Concrete
L_{cr}	Cracked length
l_d	Embedment length of steel bar in concrete
L_{ef}	Effective span length
l_n	Length of clear span length measured face to face of supports
kips	Imperial unit of force equal to 1000 pounds-force
Kg	Kilo grams
kg/m^3	Kilo gram per cubic meters
KN	Kilo Newton
KPa	Kilo Pascal
Ksi	Size effect factor
k_{cs}	Coefficient of creep and shrinkage in long-term deflection calculations
K_p	Final slope of the compressive stress-strain curve
max	Maximum
min	Minimum
ml/kg	Millilitre per kilo gram
mm	Millimetre
$mm/mm\ ^0K$	Millimetre / millimetre grade Kelvin
MM	Moisture migration
MoE	Modulus of elasticity
MoR	Modulus of rupture (flexural tensile strength)
MPa	Mega Pascal
M_a	bending moment due to servivce loads (service moment)

M_a / M_u	Ratio of service moment to the ultimate moment capacity of reinforced concrete section
M_{cr}	Cracking moment of reinforced concrete section
M_{cr} / M_u	Ratio of cracking moment to the ultimate moment capacity of reinforced concrete section
M_{max}	Maximum bending moment at critical section
M_u	Ultimate bending moment of reinforced concrete section
m_1	Weak axis of the material
m_2	Strong axis of the material
m^3	cubic meters
$M–\kappa$	Moment- curvature
N	Vector of applied loads
N-SCC	Normal self-compacting concrete
N/mm^2	Newton per square millimetre
N(t)	Resisting force (reaction) in restrained shrinkage test
OPC	Ordinary Portland Cement
OPKS	Oil Palm Kernel Shell
pcf	Pound per cubic inch
PET	Poly-Ethylene Terephthalate
PFA	Pulverised Fuel Ash
PL60-11-3L	Type of strain gauge to record the strain variation in concrete surface
psi	Pounds per square inch
P_{cr}	Tension force at first cracking under direct tension
RC	Reinforced concrete
RH	Relative Humidity
RILEM	Reunion Internationale des Laboratoires et Experts des Materiaux (International Union of Laboratories and Experts in Construction Materials, Systems, and Structures)
RMS	Road and maritime services
RTA	Regional Transportation Authority
RVDT	Rotary variable differential transformer
r_{ec}	Reduction factor of the compressive strength
R_{elec}	Electrical resistivity
r_{et}	Reduction factor of the tensile strength
R_{hm}	Rebound value (Schmidt hammer)
R_r	Ratio of the rib height to the rib spacing in ribbed bar
S	Bar spacing
s	Slip of steel bar in concrete
SCC	Self-compacting concrete
SFRC	Steel Fibre Reinforced Concrete
SHCC	Strain Hardening Cementitious Composites

SLWAC	Sand Light-Weight Aggregate Concrete
SP	Super Plasticiser
S-SCC	Self-compacting concrete containing Polypropylene fibre
STS	Splitting tensile strength
S_0	bond transfer length in short-term loading
S_0^*	bond transfer length in long-term loading
s_m	Slip of steel bar in concrete at peak bond stress
S_r	Final average crack spacing
s_r	Rib spacing in steel bar
t	Time
T_{max}	Ultimate bond force
t_c	Age of concrete where moist-curing ends in days
UDL	Uniformly distributed load
UHPFRC	Ultra High-Performance Fibre Reinforced Concrete
UNSW	University of New South Wales
UPV	Ultrasonic Pulse Velocity
UTS	Universtity of Technology Sydney
U_i	Elastic strain energy
V/S	Ratio of Volume to drying surface area of concrete specimen (Hypothetical thickness)
vol.%	Volumetric percentage
V_{air}	Entrained air content by volume
V_p	Loading rate in pull out test
$V_{\Delta W}$	Rate of weight loss of shrinkage specimen with time
w	Crack width
w/c	Water/cementitious material ratio
WFLA6-11	Type of strain gauge to record the strain variation in steel bars
w_a	Applied service load
w_c	Crack width at the complete release of stress
W_i	Applied work of external force P
w_{max-t}	Maximum crack width at time t
W_0	Initial weight of shrinkage specimen
γ	Density
γ_{RH}	Coefficient of relative humidity in creep coefficient calculation
γ_{VS}	Coefficient of hypothetical thickness in creep coefficient calculation
γ_{t0}	Coefficient of loading time in creep coefficient calculation
γ_{xy}	Shear strain component in plane x and direction y
γ_{yz}	Shear strain component in plane y and direction z
γ_{zx}	Shear strain component in plane x and direction z

ΔU	Vector of current nodal displacement
Δ_{cr}	Deflection due to creep effect
Δ_e	Flexural elastic deflection of slab
Δ_{e-14}	Flexural elastic deflection of slab based on the modulus of elasticity at 14 days
Δ_{e-28}	Flexural elastic deflection of slab based on the modulus of elasticity at 28 days
δ_i	Crack opening displacement
Δ_{inc}	Incremental flexural deflection
Δ_{ins}	Instantaneous flexural deflection
Δ_{ins-14}	Flexural instantaneous deflection of slab subjected to loading at age 14 days
Δ_{i-t}	Flexural deflection of point i at time t
$(\Delta_{ins} / \Delta_e)_{14}$	Ratio of flexural instantaneous deflection to the elastic deflection based on the modulus of elasticity at 14 days
$\Delta_{ins-14} / \Delta_{e-28}$	Ratio of flexural instantaneous deflection at 14 days to the elastic deflection of slab based on the modulus of elasticity at 28 days
Δ_{long}	Long-term flexural deflection
$\Delta_{long} / \Delta_{ins}$	Ratio of long-term to instantaneous flexural deflection
Δ_{sh}	Deflection due to shrinkage (autogeneous and chemical shrinkage)
Δ_{sus}	Time-dependent deflection under sustained loading
Δ_{tmp}	Temperature induced deflection
Δ_{tot}	Total flexural deflection
$\delta\kappa_{0.ts}$	Average instantaneous curvature
ΔW	Weight loss of shrinkage specimen
$\Delta W/W_0$	Ratio of lost weight to the initial weight of shrinkage specimen
Δ/L_{ef}	Flexural deflection limit of beam and slab
Δ_1	Vertical deflection of slab at mid-span
Δ_2	vertical deflection of slab at the border of high moment region
Δ_{e1}	Calculated elastic deflection of slab at mid-span
Δ_{e2}	Calculated elastic deflection of slab at the border of high moment region
Δ_{1-SS}	Flexural deflection at midspan of simply supported slab
Δ_{1-FE}	Flexural deflection at midspan of fixed supports slab
Δ_{2-FE}	Flexural deflection at the border of high moment region in fixed supports slab
Δ_{2-SS}	Flexural deflection at the border of high moment region in simply supported slab

ε	Strain
ε'_c	Corresponding strain to the maximum compressive strength of concrete
ε_{cr}	Creep strain
$\varepsilon_{csd.b}$	Basic drying shrinkage strain
$\varepsilon^*_{csd.b}$	Final drying basic shrinkage strain
ε^*_{cse}	Final autogeneous shrinkage strain
ε_e	Elastic strain
ε_p	Plastic strain
ε_s	Tensile strain in steel bar
ε_{sh}	Shrinkage strain
ε_z	Normal strain component in z direction
ε_{cse}	Autogeneous shrinkage strain
ε_{csd}	Drying shrinkage strain

ε_{s2}	Average strain in a tensioned member
ε_y	Ultimate strain of tensile steel bar
ε_u	Ultimate strain of the compressive stress-strain curve
ε_o	Corresponding strain to the maximum compressive strength of concrete
ξ	Scalar stiffness degradation variable
κ	Curvature
κ_{sh}	Shrinkage-induced curvature
$(\kappa_{sh})_{cr}$	Shrinkage-induced curvature on a previously cracked cross section
$(\kappa_{sh})_{uncr}$	shrinkage-induced curvature in uncracked cross-section
λ	Crack spacing
$\mu\varepsilon$	Micro strain
ν	Poison ratio
ρ	Ratio of tensile steel bar in the section
ρ_b	Ratio of tensile steel bar in the section at balance condition
σ_0	Reference compressive stress of concrete
σ_e	Effective stress
σ-ε	Stress-strain
σ_c	Compressive Strength of concrete
σ_z	Normal stress component in direction z
σ_y	Normal stress component in direction y
σ_x	Normal stress component in direction x
σ_{c1}	Concrete stress away from the crack
σ_{s1}	Steel stress away from the crack
σ_{s2}	Steel stress at the crack
σ_{s1}^*	Steel stress away from the crack after all shrinkage cracking
σ_{s2}^*	Steel stress at the crack after all shrinkage cracking
τ	bond stress
$\tau_{b\text{-}average}$	Average bond stress to describe the force transfer between steel bar and concrete
τ_{max}	Peak bond stress
τ_{xz}	Shear stress component in plane x normal to z direction
τ_{yz}	Shear stress component in plane y normal to z direction
τ_u	Ultimate bond stress
ϕ_{cc}	Creep coefficient
$\varphi\ (t,t_0)$	Creep coefficient

$\phi_{c.b}$	Basic creep coefficient
ϕ_u	Ultimate creep coefficient
^0K	Degree Kelvin
$2D$	Two- dimensional
$3D$	Three-dimensional
$\%$	Percentage

ABSTRACT

Long-term deflection of concrete slabs is often the main governing design criteria to determine the appropriate thickness of the slabs to meet the required serviceability limit state. Due to the nonlinear nature of the material, predicting the long-term deflection of concrete structures is complex. Also, the complicated behaviour of concrete in the presence of reinforcement makes the problem more challenging to study.

In general, codes of practice give an overall estimation of the long-term deflection as a multiplier of the short-term or elastic deflection of concrete structures. Such estimation sometimes may lead to an entirely wrong prediction of deflection and consequently unsafe, unrealistic and unprofitable concrete design and construction.

Recent developments in concrete technology have led to produce new construction materials by significant strength and performance features. Many of these developments are engineered solutions to technical and commercial problems by either improvement of the current practices or overcoming of limitations in the existing construction technology. Lightweight and self-compacting concrete are the main two innovative concrete types used in the construction industry along with conventional concrete. This study examines and evaluates the time-dependent deflection of reinforced concrete one-way slabs made of two concrete types versus the conventional concrete.

The presented investigation comprises both experimental and analytical components. The experimental part consists of laboratory investigation of the time-dependent flexural deflection and monitoring of the strains in reinforced concrete slabs. Since lightweight concrete is very prevalent in building construction in Australia, and there are limited studies on its long-term behaviour, the current study examines the lightweight concrete slabs identical to the previously tested conventional concrete slabs (Nejadi, 2005) and self-compacting concrete slabs (Aslani, 2014) subjected to the identical long-term loading.

In addition, an analytical study consists of verification of the recorded experimental data and parametric study of the effective factors in the time-dependent behaviour and deflection of the conventional and self-compacting concrete slabs are conducted. Recently developed high-capable ATENA software is utilized in the numerical analysis. Load-deflection behaviour of the slabs under short-term loading is also recorded and compared with those of self-compacting and conventional concrete slabs.

Finally, the results of this study are used to evaluate and verify the existing and proposed models associated with the parameters that affect the flexural deflection of reinforced concrete slabs with different types of concrete.

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CHAPTER 1

INTRODUCTION

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